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Cross Sections of the Deuteron–Proton Breakup at 130 MeV: A Probe of Three-Nucleon System Dynamics

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Abstract Three-nucleon system dynamics can be investigated quantitatively by comparing observables calculated with the use of Faddeev equations with results of precise measurements. Proper description of the experimental data can be achieved only if the dynamical models include, in addition to the nucleon–nucleon interaction, subtle effects of suppressed degrees of freedom, effectively introduced by means of genuine three-nucleon forces. A large set of high precision, exclusive cross-section data for the $^1\text{H}(\text{d},\text{pp})\text{n}$ breakup reaction at 130 MeV contributes significantly to constrain the physical assumptions underlying the theoretical interaction models. Comparison of nearly 1,800 cross section data points with the predictions using nuclear interactions generated in various ways, allowed to establish importance of including both, the three-nucleon and the Coulomb forces to significantly improve the description of the whole data set.

1 Introduction

Dynamics of the three-nucleon (3N) system can be comprehensively studied by means of the nucleon–deuteron (Nd) breakup reaction. Its final state, constrained by only general conservation laws, provides a rich source of information to test the 3N Hamiltonian details. Such studies are of particular importance when components of models which account for subtle effects, like three-nucleon force (3NF) influences on the 3N system observables, are under investigation. Nowadays, precise predictions for observables in the 3N system can be obtained

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via exact solutions of the 3N Faddeev equations for any nucleon–nucleon (NN) interaction, even with the inclusion of a 3NF model [1].

The most widely used in few-nucleon studies, so called realistic NN potentials (RP) are Argonne v_{18} (AV18), charge dependent Bonn (CD Bonn) or Nijmegen I and II forces. Extension of that picture is provided by the baryon coupled-channel potential (CCP), in which one Δ -isobar degrees of freedom are allowed on top of purely nucleonic ones [2]. The most basic approach, however, stems from the effective field theory applied to the NN system. The resulting expansion scheme for nuclear systems is called chiral perturbation theory (ChPT). For the 3N system, it is numerically developed in full at the next-to-next-to-leading (NNLO) order [3,4]. All the above approaches can also be supplemented by model 3NF's. In the RP case semi-phenomenological 3NF's are used, most commonly the Tucson-Melbourne (TM99) or Urbana IX (UIX) models. In the CCP and ChPT frameworks this additional dynamics is generated naturally, together with the NN interactions. The predicted effects are, however, smaller than for the TM99 or UIX forces.

There are additional difficulties in interpretation of the experimental results by means of theoretical calculations. The most important, until recently missing feature, is the Coulomb interaction: The experiments are performed mainly for the deuteron–proton system while all calculations are strictly neglecting any long-range forces. Only in the last years, a significant step forward has been made in including the Coulomb force effects for the breakup reaction. It was first tried within the coupled-channels approach [5] and recently applied also for the AV18+UIX potential [6]. Contrary to former expectations, the influence of the Coulomb force on the breakup observables can be quite significant.

2 New Generation Breakup Experiments

To allow for conclusive comparisons between the experimental data and theoretical predictions, large sets of data are required. Unfortunately, precise measurements of the breakup reaction are very demanding and were usually limited to studies of a few isolated kinematical configurations.

Our new approach to the breakup research assumed a simultaneous measurement in a large part of the phase space by using high acceptance position-sensitive detection system. Such measurements of the $^1\text{H}(\text{d},\text{pp})\text{n}$ reaction were started at KVI at 130 MeV beam energy, providing worldwide first extensive set of the breakup cross-section data, spanned on a systematic grid of kinematical variables. Cross section values were extracted for about 80 kinematical configurations [7], giving in total nearly 1,800 experimental points. The data covered a substantial fraction of the phase-space and allowed to conclude on importance of different pieces of the nuclear dynamics in describing the whole data set.

The role of additional dynamics in the breakup cross section is recapitulated in a global approach in Fig. 1. The relative difference of the experimental and theoretical cross sections, $(\sigma_{\text{exp}} - \sigma_{\text{th}})/\sigma_{\text{exp}}$, was determined and plotted as a function of E_{rel} , the kinetic energy of the relative motion of the two protons. Combining the AV18 potential with the UIX 3NF (Fig. 1, left panel, triangles) significantly improves the data description in almost the whole range of E_{rel} but the smallest relative energies, where it drives the predictions away from the data.

In comparisons of our results we were faced with quite substantial disagreements at low values of E_{rel} . Only with the inclusion of the Coulomb force into calculations in the coupled-channels approach, they were mostly explained and removed [8]. A consistent theoretical treatment of phenomenological 3NF and Coulomb force has been achieved only recently [6] and allows to investigate the role of both effects on the same level of accuracy. In Fig. 1 (left panel, squares) impact of the Coulomb force effects on the breakup cross sections can be inspected. While at large E_{rel} the long-range electromagnetic force essentially does not influence the data, it strongly reduces the disagreements at small E_{rel} values. Only with such a large set of the breakup data significance of the Coulomb force effects could have been proven and their behavior traced over the phase space [8]. It has been also established that even after including the Coulomb force there is still room for 3NF effects. The resulting total action of both dynamical ingredients supplementing the pure NN interaction can be seen in Fig. 1, right panel. One observes that at small E_{rel} values too strong action of the Coulomb force is compensated by 3NF effects, leading to a very good agreement between the data and the theoretical cross sections. The discrepancies remaining at large E_{rel} values hint at some still unresolved problems in our understanding of the 3N system dynamics, e.g. non-complete modeling of 3NF structure.

To study the Coulomb force effects in some depth, a new experiment has been performed at the Research Center Jülich (FZJ), using the deuteron beam of 130 MeV extracted from the COSY synchrotron and the detection system covering the range of very forward polar angles. The cross section values have been obtained

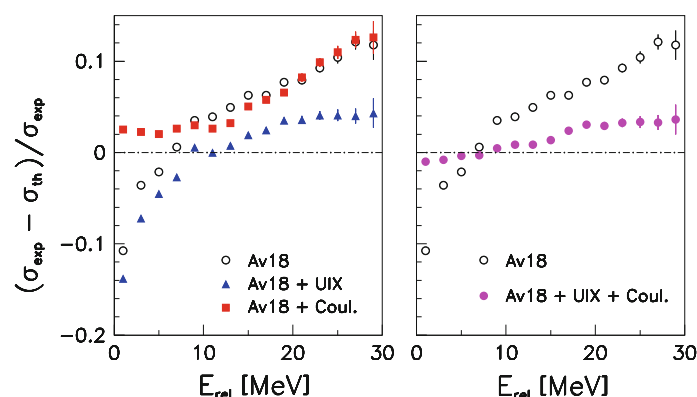


Fig. 1 Relative discrepancies between the experimental data and the theoretical predictions of the breakup cross sections as a function of the kinetic energy of the relative motion of the two breakup protons. The results for the pure AV18 NN potential are shown in both panels as empty circles. *Left panel* Action of the UIX 3NF (triangles) and of the Coulomb force (squares), when included individually with the AV18 in the calculations. *Right panel* Combined action of the above two effects (full dots)

at almost 2,400 points, with the upper angular limit overlapping the acceptance of the KVI experiment. An excellent agreement between the two data sets is achieved [9], although they stem from completely different measurements and normalization procedures. It has been confirmed that only the calculations which do include the Coulomb interaction are able to correctly reproduce the data in the phase space region very sensitive to influences of that piece of nuclear dynamics. This agreement can be considered as a proof of certain maturity of including the Coulomb force effects in the theoretical calculations.

3 Summary

Studies of the breakup reaction over a large part of the phase space are shedding light on the role of various aspects of the 3N system dynamics. After the pioneering experiments, further data sets are being acquired at several beam energies (see e.g. Ref. [10]). They present a general success of the modern calculations in describing the data. However, possibly complete theoretical treatments, including all important ingredients (3NF, Coulomb interaction, relativistic effects), as well as progress in ChPT, are very important for better understanding of complexity of the nuclear dynamics.

The cross-section data are supplemented with equally large sets of various analyzing powers and measurements of even higher-order polarization observables (see Refs. [11, 12] and references therein). Certain discrepancies observed in those observables are hints of problems in the spin part of the current models of 3NF. More experiments to study 3N system dynamics are planned at several laboratories, including the next step—continuation of the few-body system studies in the four-body environment.

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